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AN ONLINE ACQUISITION SYSTEM FOR A SECOND ORDER MECHANICAL SYSTEM (R.U.B.E.)

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Abstract

Students often are presented with measured laboratory data which is not tainted by real-world measurement issues such as noise, quantization error and poor sensor sensitivity. The students then perceive the "measurement world" as very much like the analytical theoretical equations that are presented in the classroom environment. This is often done to illustrate a particular theoretical concept (and not "cloud the issue" with real-world, contaminated data). The student then grasps the one concept of interest but is shielded from the actual measurement environment that typically exists.

A second order mechanical system is operated in an online, internet controlled experiment where the displacement and accelerations are measured with a variety of different transducers. The selection of transducers spans the range of poor transducer sensitivity, noisy measurements, inadequate resolution and clipped signals. The students must collect the data and process it to numerically integrate and differentiate the displacement and acceleration measurements. A variety of different issues must be addressed in order to cleanse the data of real-world measurement contaminants – filtering, smoothing, bias adjustment are a few of the tools that can be used.

The system has variable mechanical parameters—it changes every time it is operated so that no two sets of data are alike (variable input, variable mass, variable stiffness). This forces each student to process his/her own data, as it will be slightly different from data sets collected by other students. The RUBE (Response Under Basic Excitation) is described along with the supporting tools that assist the student in the evaluation of the acquired data.

Problem & Approach Taken

Many times students do not clearly understand the need for basic STEM (Science, Technology, Engineering, Mathematics) material. Courses in the early part of their educational experience lay the necessary foundation for upper level courses. However, the students never realize the importance of this material since they are taught the material without any real-world, practical application. Thus, the student has no initiative to retain the material and try to integrate it into their knowledge data base. The cartoon in Figure 1 is a common theme heard time and time again by just about every professor in regards to STEM material.

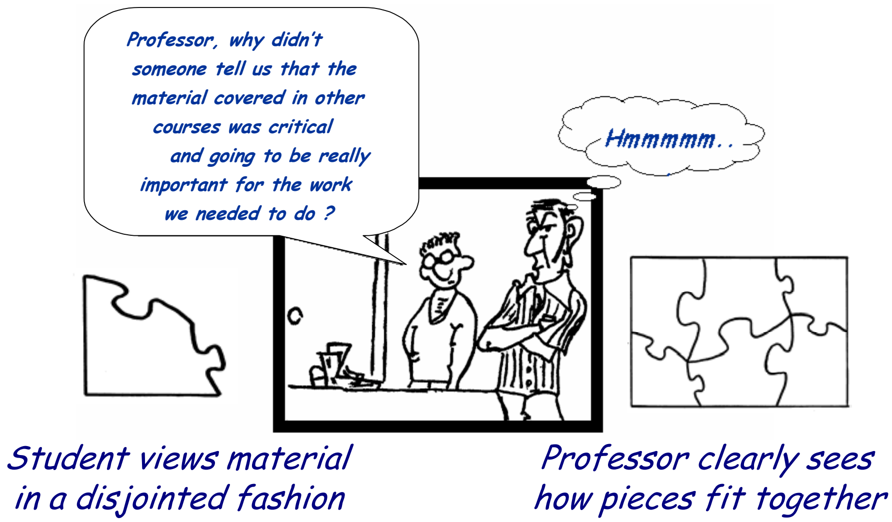


Figure 1 – Professor vs. Student View of Material Presented

In order to try to deal with this issue, a different approach has been applied for a Dynamic Systems course. A series of modules have been developed that try to integrate the basic underlying material that is necessary to solve these problems [1]. These modules have been deployed in pre-requisite courses such as Differential Equations (sophomore), Mechanical Laboratory (junior), and Numerical Methods (junior) to provide tools necessary to solve project based problem in Dynamic Systems (senior). The modules have addressed topics such as numerical integration/differentiation [2,3], visualization tools for understanding 1^{st} and 2^{nd} order system response characteristics [4], issues related to understanding complex frequency response characteristics [1], development of a virtual measurement system [5], and development of a laboratory measurement system [6]. These modules have been inserted into the pre-requisite courses to enable the students to develop skills on a continuing project that is threaded through the development of the material across several pertinent, related courses. This culminates in a Dynamic Systems project [7,8] that forces the students to integrate many previously learned skills in a meaningful manner.

The Virtual Measurement System (VMS) [5] provides the students with an invaluable tool to understand the measurement system problems that must be faced – but every one of the measurement contaminants can be controlled with the VMS. The online measurement system, RUBE, is an actual measurement system which provides a broad spectrum of issues that are typically encountered in practice. The details of RUBE are presented in this paper. The online acquisition system enables the students to collect measurements with a variety of issues for a second order mechanical system. The actual measurement system has a "personality" that forces the students to "think outside the box" in order to evaluate the system. The majority of the material described above is also available on the Dynamic Systems Webpage [9]. The webpage is shown in Figure 2 with the major items of interest identified.

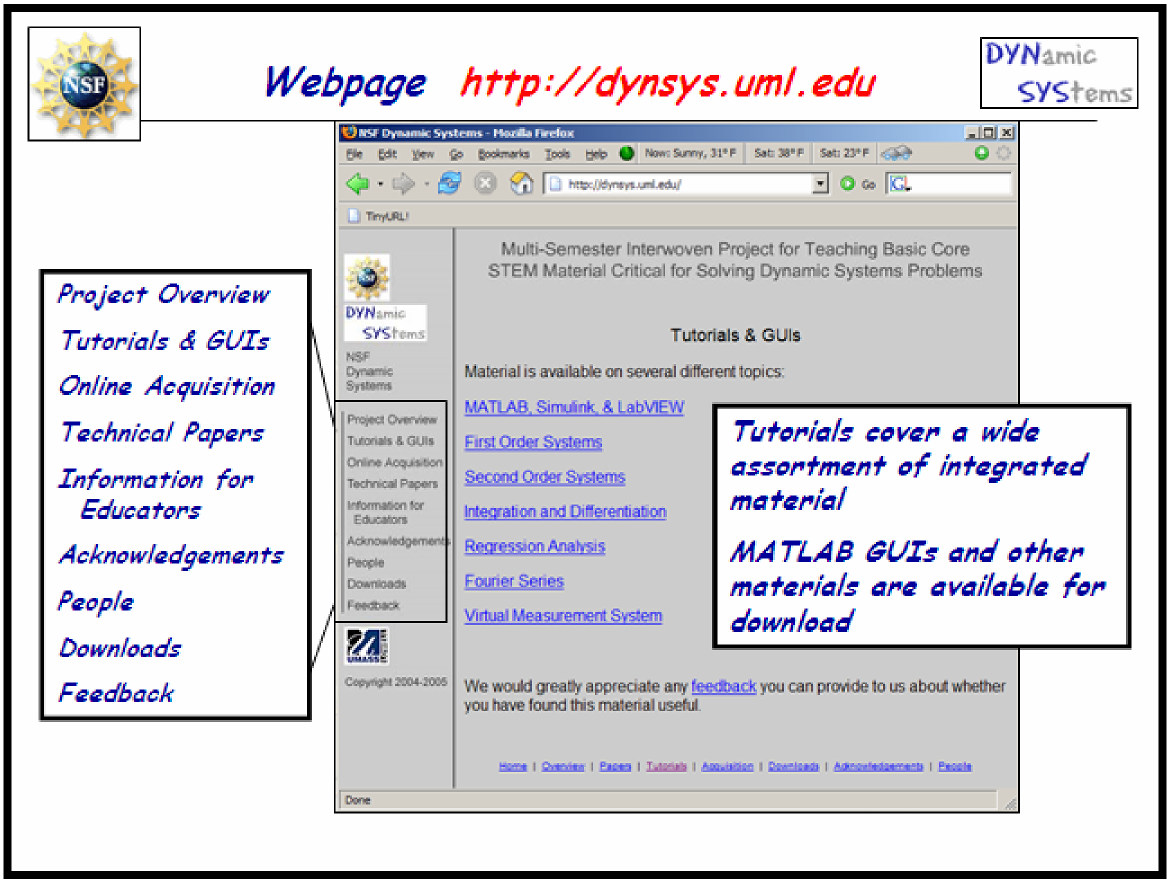


Figure 2 – Dynamic Systems Webpage Information

This paper addresses only a small portion of the entire set of information that has been developed. The following sections describe the Virtual Measurement System as well as the online measurement system developed as part of the overall effort on this project.

Virtual Measurement System

The aspects of the Virtual Measurement System (VMS) are only very briefly summarized here. More detailed information can be found on the Dynamic Systems Webpage [9] and have been documented in Reference 5. The VMS actually replicates the RUBE data acquisition system with many of its "peculiarities".

A Simulink model (and the graphical user interface "GUI" used to control it) attempts to analytically replicate the real-life problems seen with data from these transducers. These problems can then be more easily identified and understood. The dynamic system modeled is a simple single-degree-of-freedom (SDOF) second-order system. To this basic model, components are added which simulate the output from an LVDT and accelerometer placed on this system. Various corrupting factors can then be added and varied to observe the resulting effect on the output. The use of a simple RC circuit low-pass filter to reduce higher frequency noise can also be explored. The basic Simulink model is shown in its entirety in Figure 3. It consists of three basic sections: the central portion which describes the SDOF second-order dynamic system (in blue), the simulated accelerometer output (in red), and the simulated LVDT output (in green). The properties of these various components can be altered using the GUI which is shown in Figure 4. This enables the user to have complete control over the features of interest.

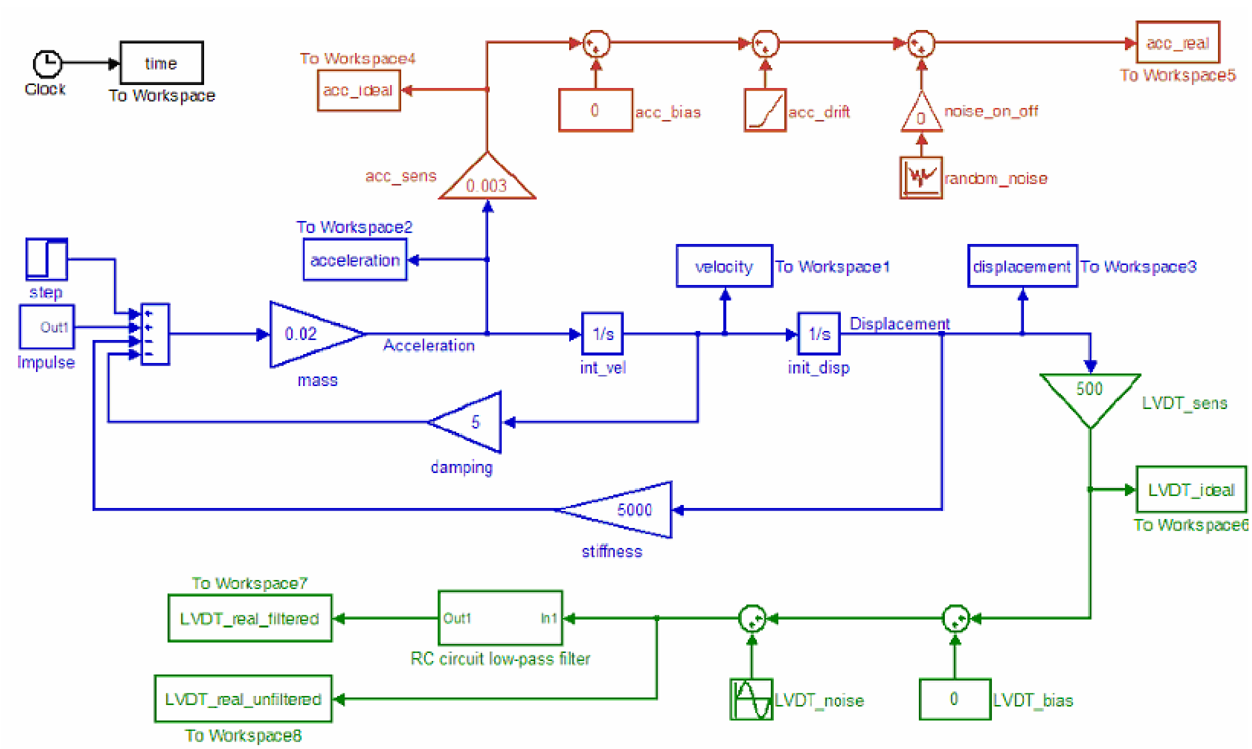


Figure 3: Complete Virtual Measurement System (VMS) Simulink Model

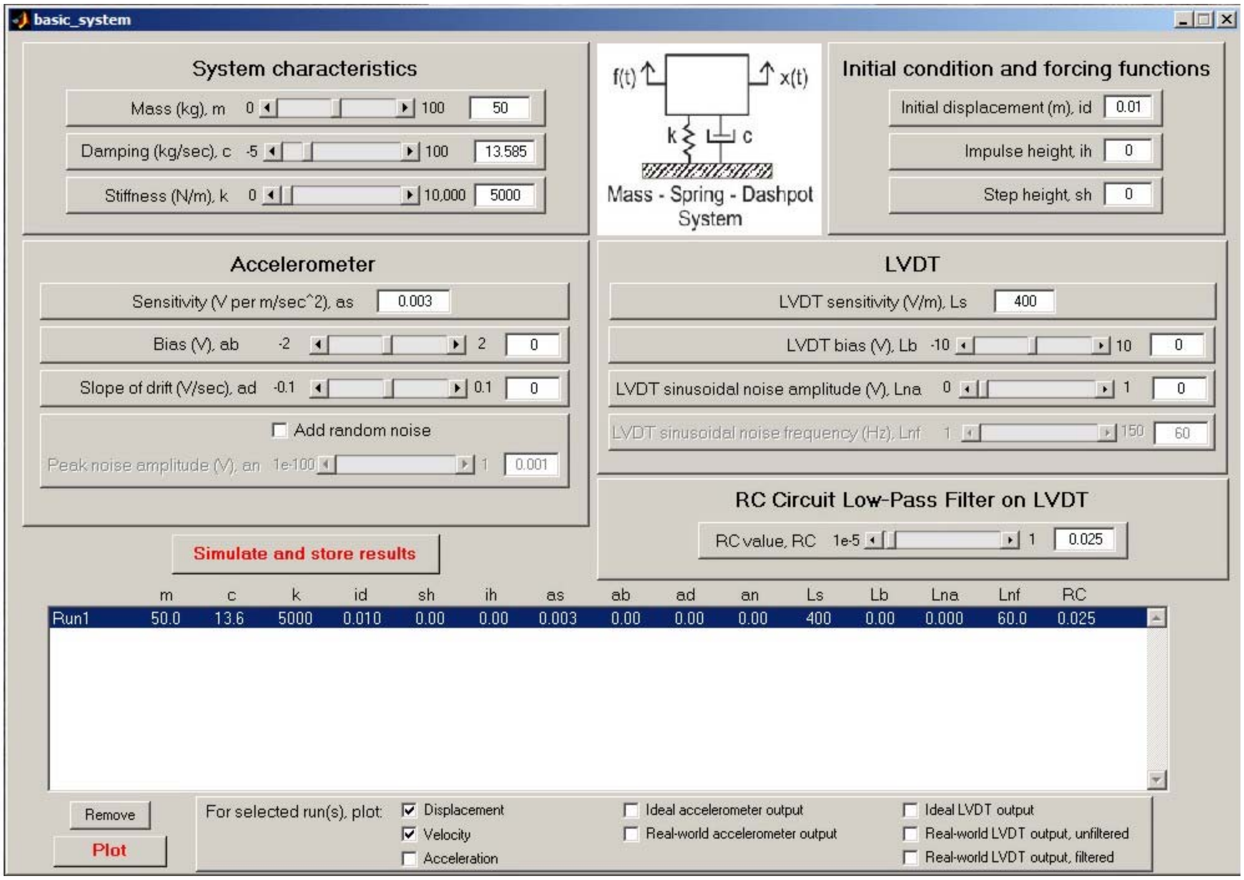


Figure 4 - Graphical User Interface of Virtual Measurement System

Response Under Basic Excitation (*RUBE*) – Physical System Characteristics

RUBE was developed to address a variety of measurement issues typically faced. These span the spectrum of the usual measurement contaminants that are seen in a real measurement situation. Using the RUBE system data, students can characterize the system from the measured response, use these identified properties to simulate the system response, perform numerical integration/ differentiation of displacement and acceleration data, as well as other engineering analyses. The processing of data, system characterization and other analyses have been presented in other papers [1-8], the intent of this paper is to describe the basic RUBE system configuration.

The system is a second order mechanical mass, spring, dashpot system that can be subjected to initial displacement and impulsive excitations. The mass and stiffness are variable parameters that are allowed to change each time the system is excited. The response of the system is measured using displacement and acceleration transducers to capture the dynamic response of the system. A data acquisition system is provided for the acquisition of the response of the system and is available as an online experiment [9] along with supporting materials. An overview schematic of the online measurement system is shown in Figure 5.

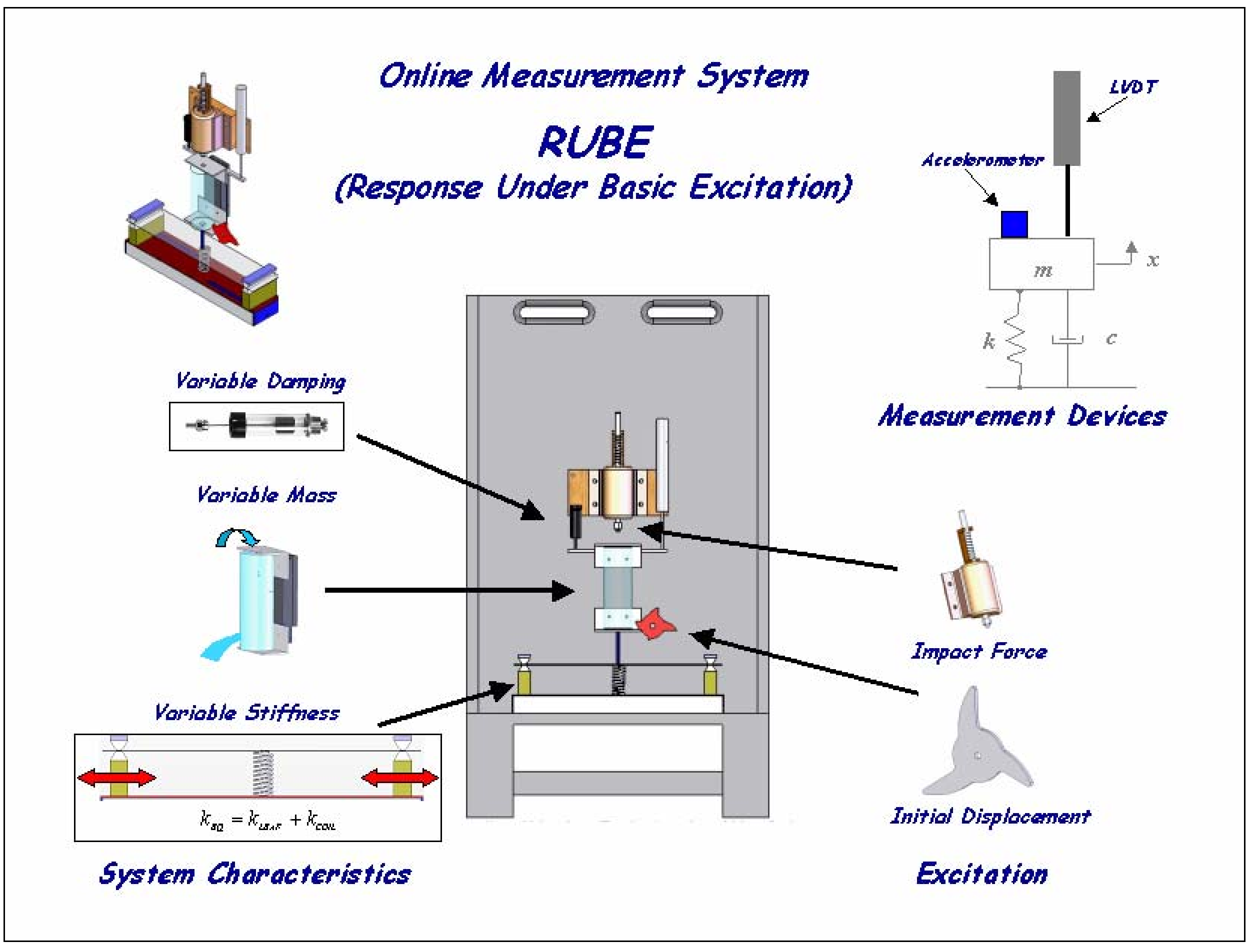


Figure 5: Schematic Overview of the RUBE System

A larger view of the overall system as well as an isometric view of the system are shown in Figure 6.

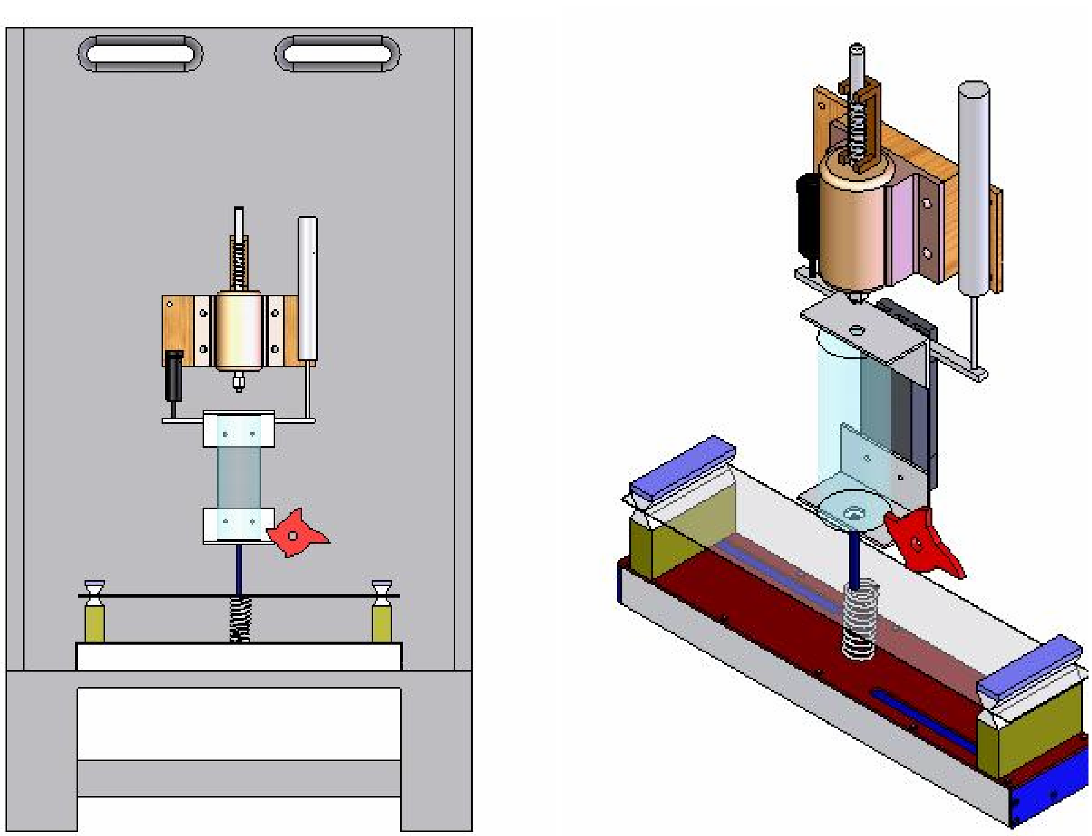


Figure 6: Schematic Overview of the RUBE System

This online experiment allows the user to collect data on the motion of a second-order mass-spring-dashpot system. The properties of the system vary with time—the moving mass of the system includes a small water tank which fills and gradually drains, and the spring portion of the system includes a leaf spring which changes in length each time the system is activated. In addition, three different initial displacements are available as inputs to the system along with impulsive excitation. Consequently, each user of the system will obtain slightly different results. Multiple different transducers are used to collect acceleration and displacement data for the motion of the system. Good transducers are available, which provide relatively clean data. However, "bad" transducers—contaminated by noise, drift, or bias—are also used.

Mass Related Components

The variable mass is achieved by using a water reservoir to provide a constantly changing mass of the system. This variable mass allows the total mass of the system to vary by approximately 15%. Figure 7 shows the mass component. The moving mass of the system consists of the sum of the mass of the water and the mass of all of the other moving parts of the system. The masses of some system components are given in Table 1.

The water tank has an inner diameter of 2.4 inches, and a maximum possible water height of 4 inches. The height of the water in the tank for each run can be determined from the video/photograph of the system which can be downloaded after the experiment is performed. Though the level of water in the tank is changing continuously, the mass of water in the tank only changes at an average rate of 0.1% during one system run.

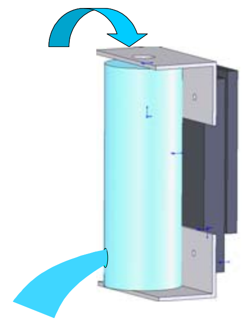


Figure 7: Variable Mass

Table 1: Some Weights Associated with the Mass Component of the System

Component	Weight (Ounces)
Water Reservoir (with valve)	1.73
Inlet hose	0.54
Outlet hose (including water)	0.18
Linear bearing	28.80
Brackets, nuts, washers, etc.	13.56

Stiffness Related Components

A variable spring stiffness is achieved with a variable length leaf spring supported with a coil spring. The variable spring stiffness allows the total spring stiffness to vary by approximately 20%. The leaf spring length is adjusted by a rack and pinion system that adjusts the support location for the leaf spring. A visual indication of the distance between the supports is identified by a scale. The leaf and coil spring arrangement is shown in Figure 8. The stiffness related components consist of a coil spring and a leaf spring as shown in Figure A2. The coil spring is fixed in dimension but the leaf spring has a variable length (between 9 to 14 inches) and is changed every time the system acquisition system is initiated. The properties of the coil spring and leaf spring are shown in Tables 2 and 3, respectively.

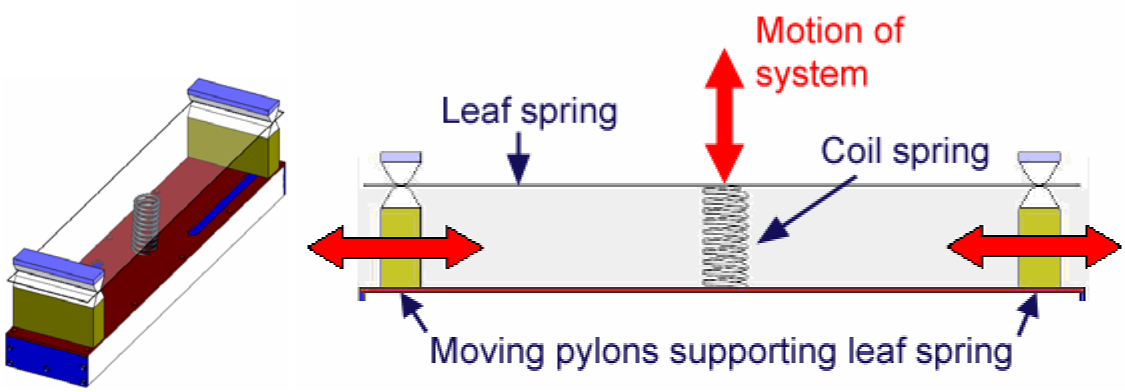


Figure 8: Leaf Spring/Coil Spring Arrangement

Table 2: Properties Associated with the Coil Spring

Property	Value
Spring material	Round steel music wire, ends closed and ground
Overall Length	2.46 in
Outside Diameter (OD)	0.54 in
Wire Diameter (d)	0.049 in
Number of Coils	4.32

Table 3: Properties Associated with the Leaf Spring

Property	Value
Material	Aluminum
Modulus of elasticity	1.00E+07 psi
Yield strength	50000 psi
Fatigue Strength (500,000,000 cycles)	20000 psi
Length	9 in to 14 in
Thickness	0.032 in
Width	4 in

Effective stiffness characteristics can be determined from a Dynamic Systems textbook, from material on mechanical systems, or from any Design of Machine Elements textbook or other Mechanical Engineering handbook. In addition to analytical methods for determining these stiffnesses, a set of data on the leaf spring was collected for various effective lengths and is shown in Table 4 and plotted in Figure 9.

Leaf Spring Span -->	L = 10 inches		L = 11 inches		L = 12 inches	
	Deflection	Force	Deflection	Force	Deflection	Force
	0	0	0	0	0	0
1	0.07	0.35	0.104	0.42	0.108	0.34
2	0.142	0.73	0.198	0.8	0.21	0.66
3	0.219	1.11	0.272	1.08	0.302	0.96
4	0.277	1.43	0.355	1.42	0.407	1.28
5	0.345	1.76	0.431	1.7	0.503	1.58
6	0.42	2.14	0.502	1.97	0.599	1.86
7	0.478	2.43			0.7	2.16
8	0.538	2.72			0.804	2.46
9					0.902	2.72
10					1	2.98

Leaf Spring Span -->	L = 13 inches		L = 14 inches		L = 15 inches		L = 16.4 inches	
	Deflection	Force	Deflection	Force	Deflection	Force	Deflection	Force
	0	0	0	0	0	0	0	0
1	0.104	0.26	0.121	0.24	0.116	0.18	0.051	0.06
2	0.202	0.5	0.203	0.4	0.206	0.34	0.1	0.12
3	0.304	0.76	0.302	0.62	0.309	0.5	0.199	0.24
4	0.405	1	0.404	0.82	0.4	0.64	0.297	0.38
5	0.496	1.22	0.506	1.02	0.504	0.8	0.404	0.5
6	0.604	1.48	0.606	1.2	0.606	0.96	0.507	0.64
7	0.702	1.68	0.7	1.38	0.707	1.1	0.604	0.76
8	0.807	1.92	0.806	1.56	0.802	1.24	0.701	0.82
9	0.904	2.11	0.898	1.74	0.904	1.4	0.805	0.98
10	1	2.31	1	1.9	1	1.54	0.905	1.08

Table 4: Leaf Spring Stiffness Measurements

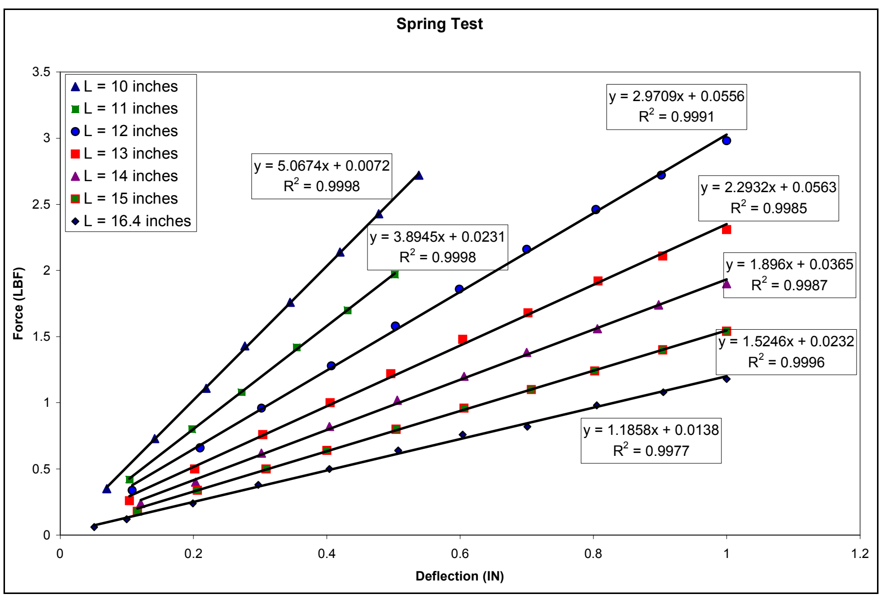


Figure 9: Force Deflection Data for Leaf Spring

Dissipative Related Components

Dissipative forces are provided by an air dashpot with variable bleed orifice; the entire system is guided by a low-friction linear bearing system which is a very small portion of the entire dissipative force. These elements are shown in Figure 10.


Figure 10: Dissipative Elements

Excitation Devices

The possible input excitations are a displacement provided by a cam with variable length sprockets (different displacement inputs) and an impulsive force provided by a solenoid device. These are shown in Figure 11. The magnitude of the initial displacement for each run can be determined from the LVDT displacement data. Nominally, the initial displacements are 0.25 in, 0.375 in and 0.5 in but these displacements change with the varying effective stiffness.

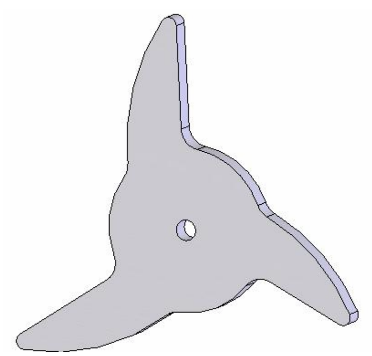
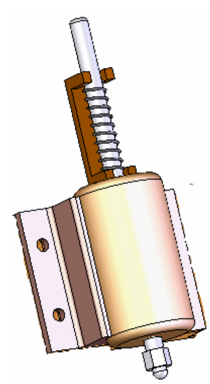



Figure 11: Excitation Devices of the RUBE System

Instrumentation

Four transducers obtain data from the system through the digital data acquisition system: one LVDT (Linear Variable Displacement Transducer) and three accelerometers of varying sensitivity; these are listed in Table 5.

Table 5: Transducer Sensitivity

Column number in dataset	Data description	Sensitivity of transducer
1	Time (sec)	-
2	LVDT (V)	9.97 V/in
3	Accelerometer 1 (V)	10.4 mV/g
4	Accelerometer 2 (V)	92.9 mV/g
5	Accelerometer 3 (V)	994 mV/g

The accelerometers used have an order of magnitude increase in sensitivity from nominal values of 10 mv/g to 1 V/g. The accelerometers weigh 0.12 oz, 0.15 oz and 0.28 oz, respectively. The LVDT has a nominal sensitivity of 10V/in and the LVDT core weighs approximately 0.52 oz. Also, the third accelerometer has a 4^{th} order Butterworth filter with a 25 Hz cutoff frequency applied to the data and therefore will experience some amplitude/phase distortion in the data.

Response Under Basic Excitation (*RUBE*) Online Data Acquisition System

The RUBE online acquisition system graphical interface is shown in Figure 12. The LabVIEW [10] interface allows the user to gain control of the interface and run the experiment. If another user has control of the experiment then a one minute time warning is given to allow the next user to gain control of the system. The user has the ability to look at any one or all of the transducers used for the measurement system. The interface provides flexibility to interrogate the measurement. The output data and a video clip of the actual data run are accessible from a separate web address that allows the user to access his/her data at any time. Some of these features are highlighted in Figure 13. In addition, a large set of previous runs that have been made are stored on the server so that users can also access previously collected data. This is useful especially when the internet traffic to the system is high and the user experiences a long wait due to numerous users waiting to access the system. A photograph of the RUBE System is shown in Figure 14.

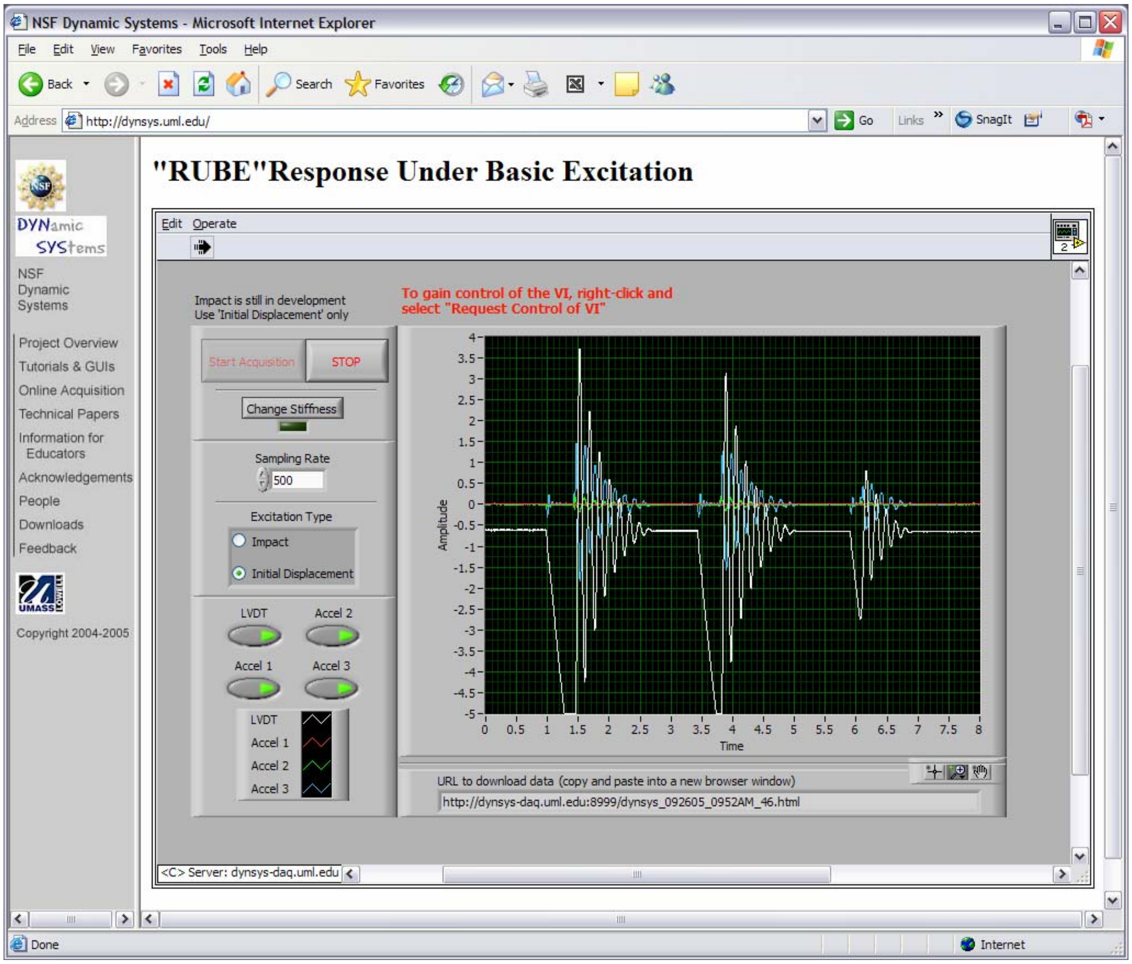


Figure 12 – LabVIEW Interface of RUBE MCK System

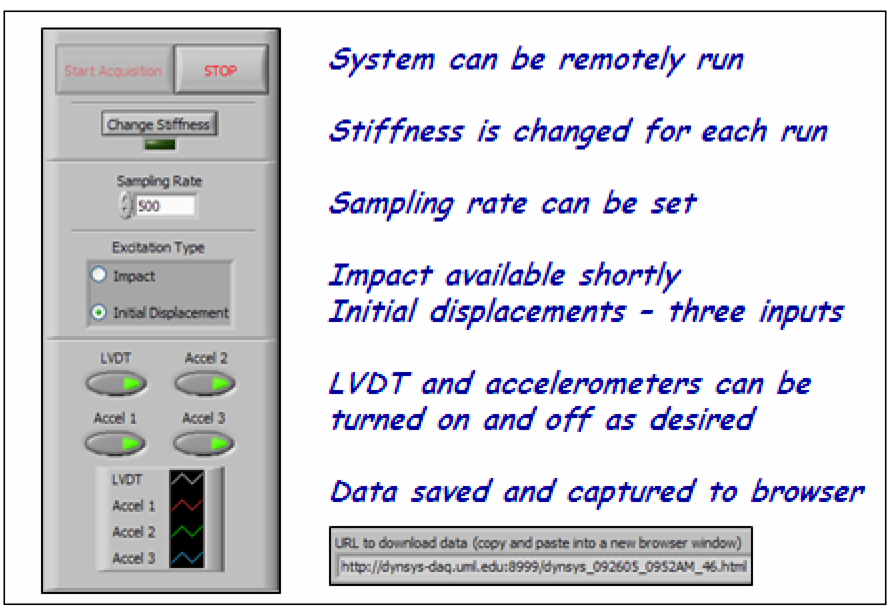


Figure 13 – LabVIEW Interface of RUBE MCK System – Detailed Controls

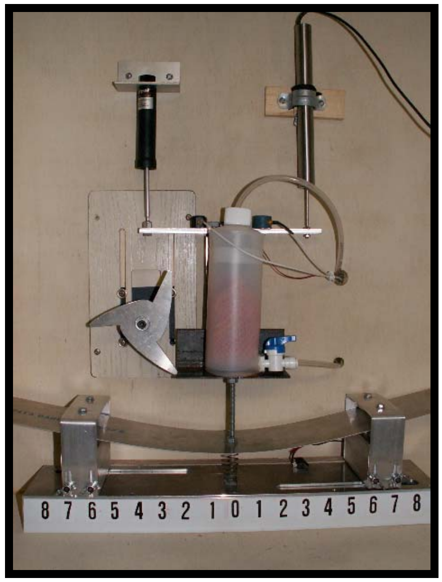
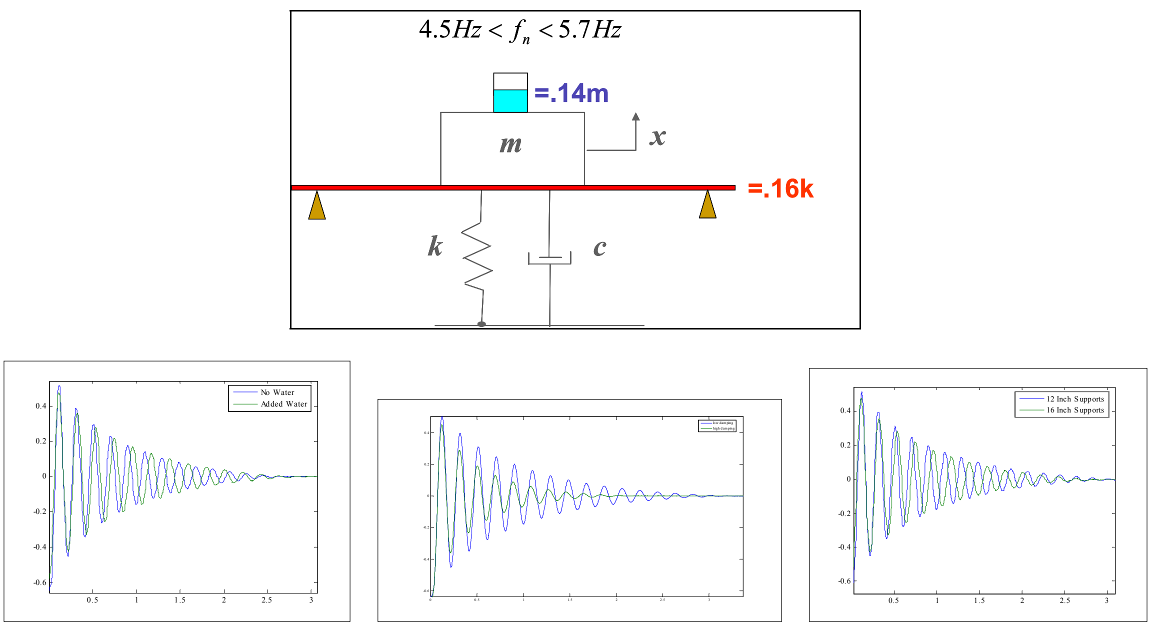


Figure 14: RUBE Mechanical MCK System

The RUBE system feature is that every time the system is run, different mass-damping-stiffness values exist. This allows students to each use the system and obtain unique characteristics that they must evaluate to determine the system characteristics – no two solutions are exactly alike. The variability on the system generally has between 10% to 20% variation in each parameter. This variation is shown in Figure 15 for identification of ranges that are typically experienced. In addition, three typical variations in response due to the individual variations in mass, damping and stiffness are shown from the design of the initial system.

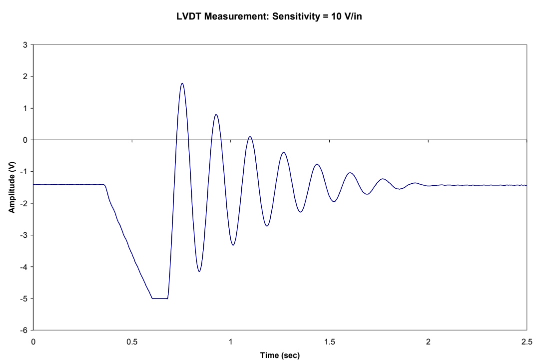


(Variation in response due to the design variables are in order of mass, damping, and stiffness, respectively)
(Specific values are not intended to be read in plots – only a conceptual overview of the range of values is intended)

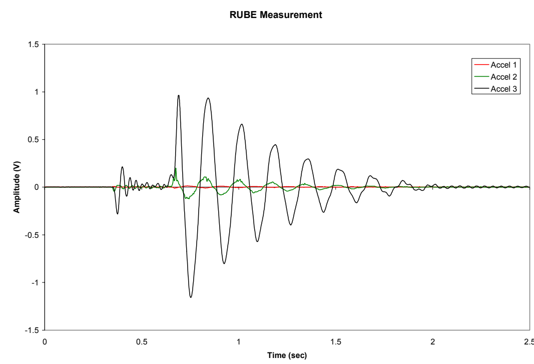
Figure 15 – Schematic of Range of RUBE System Parameters and Effect on Response

Typical RUBE Data

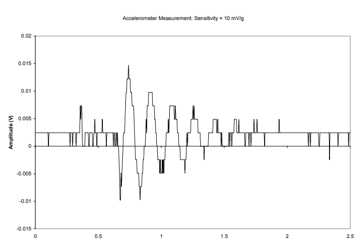
In order to further describe the RUBE system, a set of typical data is presented. The system stiffness characteristics were reset and a data set was collected. While the system is greatly improved over earlier version of the system, there are still issues pertaining to higher frequency response attributed to higher modes as well as noise on the system. The signals acquired consist of an LVDT and three accelerometers (nominally 10 mv/g, 100 mv/g and 1V/g sensitivity). While the LVDT has significant signal strength, there is a possibility of clipping of the signal for the largest of the initial displacements. Also, the accelerometers have characteristics that vary from strong, clipped signals to very weak signals that suffer from quantization errors. The response plots shown in Figure 16 clearly show all of the issues that still persist on the measured data. This presents many opportunities for the students to deal with these contaminated signals.



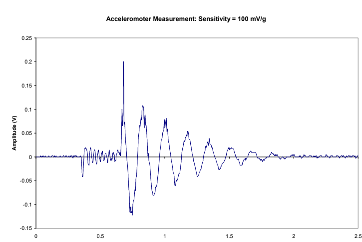
(a) LVDT data response



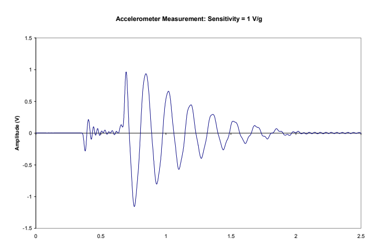
(b) All three accelerometer responses



(c) 10 mv/g accelerometer



(d) 100 mv/g accelerometer



(e) 1V/g accelerometer

Figure 16 – Typical RUBE Output Data From LVDT and Accelerometers

Conclusion

Student comprehension of basic STEM material for dynamic systems applications needs to be reinforced through active experiences. This is accomplished through an actual experimental system. The Response Under Basic Excitation (RUBE) is a second order mechanical system which is available as an online experiment. An important feature of RUBE is that the system characteristics vary every time the system is accessed. The students are provided supporting tutorial material, a virtual measurement system to explore numerous potential measurement difficulties and the actual measurement system. Overall the students have clearly indicated that the material presented has helped them to better understand the basic inherent material needed to solve the problems encountered in the measurement system. The measurement system has definitely helped the students to comprehend solutions to problems where clearly defined parameters are not available as is the case in most real-world situations.

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9. The Dynamic Systems Website, http://dynsys.uml.edu/, with assorted tutorials, graphical user tools, and online data acquisition system
   http://dynsys.uml.edu/tutorials.htm
   http://dynsys.uml.edu/Acquisition_system/onlineacquisition.htm

http://dynsys.uml.edu/downloads.htm

10. LabVIEW 7.1, National Instruments, Houston, Texas

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Tracy Van Zandt, Nels Wirkkala and Jeff Hodgkins are Graduate Students in the Mechanical Engineering Department at the University of Massachusetts. They are currently working for their Master's Degrees in the Modal Analysis and Controls Laboratory while concurrently working on an NSF Engineering Education Grant directed towards integrating STEM material critical for understanding dynamic systems response.